The Challenges of Water Recycling – Technical and Environmental Horizons

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Introduction

Drivers for Water Recycling.

Australia is a wet country – receiving enough rainfall in the drought years of 2004/2005 to provide each person with approximately 130 ML of water for one year (Trewin, 2006) – some 1500 times the average domestic requirement. However, we are heavily afflicted by both temporal and regional variability, with large amounts of water falling in consecutive years, or outside catchment areas. Previously, this has been combated by the provision of large water storage volumes for our population centres. This has led to Australia having the highest level of water storage capacity per capita in the world (4 ML per person) (DAFF, 2004), with a relatively unconstrained water use – the 3rd highest per capita consumption of water amongst OECD countries, after Canada, and the United States (Radcliffe, 2004).

In recent times, the coalescence of many different pressures – population growth, increasing urbanization, drought, reduced run-off – has placed major strains on this extensive infrastructure. Figure 1 shows how severely the drought has impacted the major population centres around Australia.

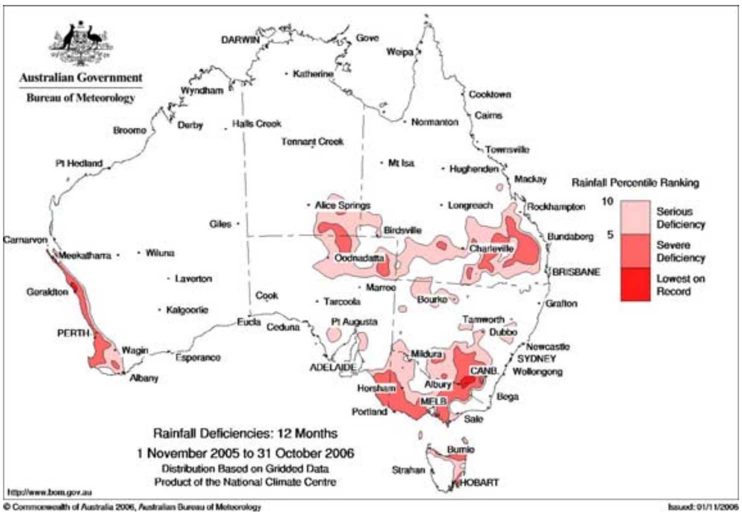

Figure 1   Rainfall Deficiency 2005/06

The level of infrastructure is reaching its natural limits, at the same time that a nation-wide drought has put further pressure on these limits. The last major round of water supply infrastructure upgrades in Australia was made some 30 years ago; the large-dam construction projects (Wivenhoe for Brisbane, Shoalhaven for Sydney, Dandalup for Perth, Thomson for Melbourne). It is now more difficult (and unreliable) to develop traditional water resource infrastructure, such as dams or groundwater extraction.

This situation calls for a dramatic shift in our water utilisation concepts. To date, all urban water infrastructure has relied on the common “linear society” concept: we extract a resource, use it (once), treat it and discharge it. This is clearly not a sustainable solution given the current pressures outlined above. The alternative option, a “circular society”, has to become the new standard for water utilisation, but also for all other vital resources. Water recycling is a common natural process and all water we use has been recycled many times.

It is against this enviro-socio-political climate that purified water recycling has emerged as one of the major contributors to a long-term sustainable water supply.

Applications for Recycled Water

Water has been historically supplied through an urban water scheme at a bulk "potable" or drinking quality. This classic case of conservative engineering design has been an enormous public health success. The bulk of water is used in applications for which this standard is excessive (Figure 2), and in the final analysis, only 1% of drinking water is actually used for drinking (National Health and Medical Research Council and Council, 2004).

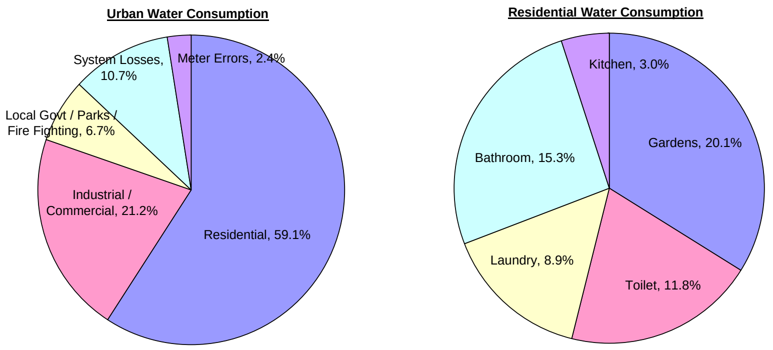

Figure 1 Urban Water Use in Australia's 22 Largest Cities

(Radcliffe, 2004)

Recycled water is already applied in bulk – for non-potable reuse – in the 30% commercial / industrial / irrigation / etc. segment, and this represents the majority of current water savings (some 26% net potable / non-potable reuse across Australia). However, recycling of non-potable water to residential users for non-potable applications has proven to be difficult and dangerous due to:

- Expense of implementing dual reticulation in new developments (not practical in existing developments); and
- Cross-contamination of potable supply (through incorrect connections installed by both plumbers and residents).

Therefore, to effectively supply purified recycled water to the majority of households, its quality must be as good as, or better than the existing supply. This then questions the need and costs for a separate reticulation system even in new developments. For this reason, the implementation of planned, potable reuse is now being frequently considered, as demonstrated by the recent Toowoomba public vote, the planning being undertaken by Goulbourn City Council and the south-east Queensland plebiscite on indirect potable reuse in March 2007.

Risks and Benefits of Water Recycling

While the water savings benefits are obvious, there are a number of other good reasons for reuse:

- Reduced nutrient and contaminant loads to waterways;
- Recovery/recycling of nutrients back to agricultural land, and minimisation of chemical fertilisers;
- Reduced stress on groundwater aquifers and surface water catchments;
- Provide an additional water source for fire fighting;

- Provide environmental flows and wetlands maintenance; and
- Improve water supply security for both potable and non-potable uses.

The consensus of technical and environmental issues adds up to a compelling case to maximise reuse of water at any level. It should also be emphasized that indirect potable water recycling is already practiced. In many cases, this is unplanned, with the wastewater discharge from one community being a significant percentage of the water source for the next community downstream. An excellent example of this is the Lower Molonglo Water Quality Control Centre in Canberra, which discharges to the Molonglo River, then the Murrumbidgee River and Burrinjuck Dam. At times, this tertiary treated wastewater from Canberra provides up to 100% of the river flow (National Coordinator for Recycled Water Development in Horticulture, 2005). Similarly, much of Europe has been using this form of water recycling for many decades.

The use of recycled water, whether planned or unplanned, poses a number of risks. Hence, water authorities have long recognised that any strategy that brings recycled water closer to direct human contact must be designed to assure public health (Radcliffe, 2004). Many risks are in common with traditional potable water delivery, but frequency of exposure may increase with the use of recycled water. Recognising and managing these risks is critical to the successful implementation of recycled water schemes.

While many other options exist for expanding our water sources – new dams, groundwater extraction, desalination, urban stormwater harvesting – water recycling will need to be part of the future sustainable water supply to our growing urban centres, well before demand exceeds supply with potentially major impacts on human health or lifestyle.

Scope of this Paper

"Water recycling" can take many forms and covers a range of issues. This paper aims to discuss primarily the scientific and technical challenges involved in recycling of domestic wastewater for reuse in potable and non-potable applications at any scale. We are well aware that community support and acceptance is also critical in achieving a successful implementation of water recycling, but for these aspects we refer the reader to contributions from other experts in the field, eg. recent research by CSIRO (Po *et al.*, 2004).

The scientific and technical issues can be grouped into three "horizons".

In the first horizon, we review the challenges that we have already addressed as a water industry community. These are the problems that have already been identified and resolved, both in theory and in practice.

In the second horizon, we address the problems that are currently confronting water recycling projects. These are the problems that we understand well and have possible solutions, but they are yet to be properly implemented in full-scale practice.

In the third horizon, we ponder the problems for which we have as yet no answer. We also speculate on potential new issues and introduce dramatically different technologies that may better address current and future challenges.

While we are only able to provide summary statements on the many aspects covered in this paper, we refer the reader to a more detailed, expanded version of this paper available on the Advanced Wastewater Management Centre web site at www.awmc.uq.edu.au .

Horizon 1: The Problems We Have Conquered

There is no doubt that water recycling is a mature technology area. The first direct potable recycling scheme was implemented over 40 years ago in Windhoek, Namibia. We are currently using the 7th generation of water recycling technology since then, including the 3rd generation of membrane based technology. This horizon relates to the key technologies that currently provide us with the capability of safe purification of domestic wastewater to pure water. These capabilities range from consistent delivery of a standardised, relatively refined feedstock, using biological treatment, through production of pure water, to dealing with residual by-products.

Horizon 1: The problems we have conquered

Issue	Classification	Description	Horizon 1 Basis
Biological treatment	Process technology	Biological treatment technologies are a fundamental part of wastewater treatment throughout Australia. They are the principal method of producing treated water, suitable for non-potable reuse, and essential to produce the raw feed for potable reuse purification equipment. Biological treatment commonly extends to tertiary treatment including nitrogen and phosphorus removal and disinfection.	Biological treatment technologies have been heavily researched and optimised, and reliably deliver high performance wastewater purification. While there are some significant ongoing research questions, we do not regard them as an impediment to delivery of purification projects or reuse of secondary purified water.
Adsorption units	Process technology	Granular activated carbon (GAC) and biological activated carbon (BAC) are widely used on secondary effluent for enhanced solids and organic removal.	Theory, design, and implementation of adsorption technologies are well understood.
Membrane technologies	Materials / Process technology	The use of membranes for the direct production of high quality, potable water has become increasingly popular in recent times, as construction and operating costs have decreased. Micro / ultra filtration, followed by reverse osmosis are now the primary membrane processes for water recycling.	While there are issues with on-going operation and maintenance of membrane technologies, and significant scope for further development (see Horizons 2 and 3), current technology is well established and suitable for current applications.
Risk management	Environment & health	The perception of risk of recycled water is one of the key factors influencing public opinion (Po *et al.*, 2004). It is recognised by authorities as being of critical importance, and therefore very good risk assessment procedures and guidelines are existing. In particular, we highlight the Australian Guidelines for Water Recycling (NRMMC *et al.*, 2006), providing a detailed framework for managing recycled water and its risks.	The accepted level of risk for recycling projects is at least the same, and often better than that used for drinking water treatment and reticulation (NCRWDH, 2005) . With strong legislation and guidelines at both the State and Federal level, we consider that risk management is a well-defined and well-managed issue for water recycling projects.
Inorganic and solid residuals	Process technology	While we can produce pure water, we also produce residuals, particularly solids and precipitates. While there is an established industry for treatment and beneficial reuse of sewage solids, water recycling by-products are not yet all well managed.	The practices in use for stabilising and handling solids are well understood and successful. As discussed later, there are however dissolved residuals particularly from membrane processes that offer additional challenges.

Horizon 2: The Current Battleground for Water Recycling

In this horizon, we discuss the problems that are currently being addressed in water recycling schemes around the world. These are the issues that may have been solved in theory or in the laboratory, but they are yet to be fully introduced into full-scale practice. Many of these challenges still need applied R&D input, leading to direct and immediate benefits.

Horizon 2: The current battleground for water recycling

Issue	Classification	Description	Horizon 2 Challenges
On-line monitoring – performance, integrity & quality	Process technology	From an established baseline, monitoring needs to (NRMMC *et al.*, 2006): • Validate (will it work?); • Monitor (is it working?); and • Verify (did it work?). Unless on-line monitoring is used, most monitoring is effectively in the last category.	Most current methods for on-line monitoring give indirect indicators (e.g., conductivity, membrane pressure). Further research is needed to relate newer methods (e.g., UV/VIS spectroscopy, electrochemical sensors) to specific quality measures.
Virus removal	Environment and health	Viruses are probably the biggest pathogenic health risk in recycled water. In order to effectively guarantee quality requirements[1], a multiple barrier, and highly precautionary approach is required.	As our body of knowledge increases, it is expected that we will refine expectations of removal by specific processes, and possibly minimise the extent of over-design without compromising health.
Inorganic fouling (ionic)	Process (materials) technology	Precipitation occurs when compounds exceed their solubility limit, and form solid compounds. This particularly happens in membrane systems as they concentrate chemicals on the retentate side. Precipitates may either directly scale on the membrane, or form particles of similar size as the membrane pores, and hence cause excessive fouling. Ionic precipitation is most common, and occurs when a combination of anions and cations combine to form an inert solid.	Since the inorganic precipitant is a combination of ions, it can be re-dissolved by removing one of the ions (eg. by pH adjustment). While this results in good management strategies (eg., chemical cleaning, additives), the problem is difficult to predict, causes increased costs, and increases financial risk. Many compounds are only identified after a problem has occurred, and research is needed to better predict precipitants and develop suitable control measures.
Adsorption and biological systems integrity	Process technology	Systems for potable reuse need a metric to indicate overall process failure. While transmembrane pressure can be used to monitor membrane systems, adsorption and biological systems have no such measure. Operation with active monitoring and control is needed to produce good product quality.	Measurement and control technologies are available, but not effectively implemented in full-scale processes. This is a research need, as chemical and biological processes are useful on their own or in combination with membrane systems.

Issue	Classification	Description	Horizon 2 Challenges
Micropollutants	Environment and health	A very complex topic, and key issue for the public (particularly EDCs and PPCPs [2]). Levels of these chemicals in purified recycled water are typically below nano (10^{-9}) gram levels. These levels are not causing any human health impact (Ying et al., 2004), but environmental and ecological impacts remain a concern.	Removal of these is quite effective in modern biological treatment processes and particularly in water purification plants. However, research is still on-going, and particular emphasis is on environmental impact of discharges such as untreated membrane concentrate.
Dissolved organic residuals	Process technology	Some 15-40 mg/L of organic material in wastewater is not degraded, and remains in the effluent, and will be concentrated by membrane processes. This has potentially an environmental impact, and may need to be removed from the concentrate stream.	Advanced oxidation and adsorption processes can remove these compounds, but capital and operating costs are high. Combinations of biological and chemical processes may be effective, but need further research.
Energy consumption and greenhouse gas emissions	Economic (process technology, materials)	Current water supply methods are very energy efficient. Reservoirs are located in high regions, and sewage plants to low regions. Therefore, for indirect potable reuse it is necessary to return it back to the higher regions. In addition, water purification and transport methods are very energy intensive. Pumping water over a distance of 200 km, with a static lift of 45 m requires 550 kWh/ML in energy consumption. Membrane treatment of secondary effluent adds a minimum of 700-1000 kWh/ML, while desalination processes require around 4000 kWh/ML. Unless the energy is generated from renewable sources, all these processes add considerably to greenhouse gas production, itself likely a main cause of climate change.	The issue of energy consumption with recycled water treatment and transport needs to be recognised as a real issue, and a driver for alternative delivery modes (than indirect potable reuse via dams). Calculations on energy efficiency and greenhouse gas emissions are well established. The challenge for industry is to ensure that the delivery of recycled water does not come at the unacceptable cost of other environmental damage. Unfortunately, crisis mode responses to severe water shortages have partially obscured this crucial connection.
Recycled water pricing & ownership	Economic	Costs of, and sale price of recycled water are highly variable, with costs often exceeding sale price. There needs to be an incentive for users to utilise recycled water, but a minimal price may encourage excessive use. Ownership is also an issue. To what extent should ownership be divided among the secondary effluent producers (councils), purifier, and bulk water suppliers (state government agencies)?	Part of the difficulty in assessing the true cost, and a realistic price for recycled water lies in a lack of transparency in costing and subsidies. While the issues involved are relatively well defined, we believe there are many issues to resolve, and the topic remains in Horizon 2.

Issue	Classification	Description	Horizon 2 Challenges
Total system optimisation	Economic	Australia's sensitive environment has lead to very strict environmental standards, with a consequently intense level of energy and resource utilisation. Concentrating pollutants, and recycling pure water would allow a number of novel optimisation methods, including relaxing secondary treatment limits, and focusing on concentrate treatment. On the other hand, trade waste discharge limits may need to be revised in light of the different water treatment and final utilisation methods.	Good background knowledge is available, as are some excellent optimisation tools. Optimal and integrated operation of each step (from water use to purification) is still a challenge though. Given the significant potential cost and environmental benefits, overall system optimisation is well worth considering as a major driver in design and operation of recycling schemes.

1. e.g., a requirement of $<10^{-6}$ disability affected life years per person, per year requires a 6 log reduction, based on rotavirus (NRMMC *et al.*, 2006).
2. EDC: Endocrine disrupting chemicals; PPCP: pharmaceuticals and personal care products.

Horizon 3: The Frontier Problems for Water Recycling

At Horizon 3, we cover some of to the currently unsolved problems in water recycling. These are the issues that, whilst not slowing the rate of implementation of water recycling schemes, are yet to be resolved. We also speculate about the possibility of some future technologies for water recycling, beyond the current preferred choice of membranes. In this area, we flag the possibilities of nanotubes and electrostatic separation in bi-polar membranes. These are topics of longer-term research projects with significant scope for substantial impacts.

Horizon 3: Frontier problems for water recycling

Issue	Classification	Description	Horizon 3 Challenges
Virus testing	Environment & health	In Horizon 2, we identified virus removal as the greatest microbiological risk to human health in water recycling. Methods for removal are emerging on Horizon 2, and are becoming well established in practice. However, the final, critical step of monitoring remains on the edge of our theoretical and practical knowledge.	There is only one Australian laboratory with the required accreditation for virus testing, and reference and indicator standards have not been fully established. There are good candidate viruses, including those impacting health, and resisting treatment methods.
Organic membrane fouling	Process technology	Organic fouling refers to the attachment of organic compounds on membrane surfaces, leading to fouling. These include macromolecules, and particulates (including microbes). Most can be treated by backwashing, but there appears to be irreversible fouling (suspected inorganic and organic), eventually requiring replacement of the membranes over 4-6 years.	It may be surprising to find this topic in the Horizon 3 section given the large amount of research and application work done in this field. However, we still consider that there is a large degree of uncertainty in the predictability and prevention of organic fouling for various membrane systems.
Inorganic fouling (non-ionic)	Process technology	Non-ionic precipitation occurs when an inorganic molecular compound simply exceeds its solubility limit, normally through reverse osmosis treatment. This has recently been identified as a problem, especially in systems with elevated levels of silicates.	Since the compounds are not made up of ions, chemical cleaning is not very effective. Deposition of silicates seems to be a major problem, with some unexpected, and as yet unexplained interactions with ions.

Issue	Classification	Description	Horizon 3 Challenges
Ecological impact of organic residuals	Environment & health	Water recycling does not cause greater discharge of organics – they simply are discharged in a more concentrated form. In low-flow situations (e.g. streams during droughts), this can have a major negative impact. Additionally, the presence of a number of pollutants in a concentrated form offers opportunities for more efficient treatment.	The impact of concentrated residual organics, and their degradation in the environment is poorly understood. This ties in with total system optimisation, since extensive construction and energy-expensive transport steps may make the solution worse than the problem.
Dissolved organic nitrogen	Process technology	Dissolved organic nitrogen (DON) is normally 1-3 mgN/L in secondary effluent. It is a complex mixture of relatively small molecules (<5000 Da) (Bowyer, 2004). It is generally only 10%-20% degradable by biological methods. It can be degraded by advanced oxidation, but this requires significant capital and operating costs.	Very little research has been done into full-scale applicable methods for DON removal. The initial approach would be to focus on the concentrate (brine) stream from RO systems since the concentrations there are much higher (typically 10-20mg/L), with lower flow rates compared to the direct treatment plant effluent.
Saline residuals	Process technology (Environment & health)	Water supplies in Australia are generally low in total dissolved solids (TDS). However, large amounts of salt are added through reticulation and usage and seawater intrusion. While reverse osmosis can remove salts from the treated stream, but they are concentrated in the brine stream. This may be easily disposed of in coastal regions, but poses major issues inland.	Given the high levels of existing inland salts, it is unlikely that this waste product will ever be valued. Additionally, there are few technological solutions apart from transport. Given the bleak outlook, and the importance of this topic, it must remain in Horizon 3 and some significant efforts are required to address it.
Source control and monitoring	Process technology	Sewer monitoring, and trade waste policies have mainly been driven by avoidance of risk to the high-capital sewer infrastructure. Water recycling plants introduce a range of new technologies (particularly membranes), that are substantially more sensitive, particularly to pollutants that may not be detected using current methods or are not yet recognised as a problem.	Surveying and evaluating upstream contributors will become more critical, given the expense and importance of recycling projects. It involves construction of a database of problematic chemicals, survey of customers, and both research, and monitoring to identify specific problem conditions.
Nanotube membranes	Materials technology	The largest expense, and highest environmental impact from membrane purification is electric power use. This is largely related to permeability of the membrane. Novel membranes based on carbon nanotubes, with exactly defined “openings” (6 water molecules wide), achieve permeabilities 100 times greater than conventional membranes (Holt et al., 2006).	This is very exciting research, and selectivity (apart from molecular size) needs to be investigated. Applications on non-pure water also need to be expanded. However, it is new research, and time to market is at least 5-10 years.

Issue	Classification	Description	Horizon 3 Challenges
Electrochemical and surface active membranes	Materials / process technology	This refers to a wide range of methods utilising electrochemical interactions. An example process utilises bi-polar membranes, which combine anion and cation selective membranes, with an applied electrical potential to produce a clear centrate stream.	While this research has reached market for concentrated streams, it is not yet applicable to dilute stream purification, and major limitations at this stage are likely the cost and practical applicability of the membranes, as well as electrical operating costs.

Conclusions

A quick glimpse at this paper would give the impression that since the tables for Horizons 2 and 3 are twice the size of the Horizon 1 table, the remaining problems are of far greater magnitude than those solved. In fact, it demonstrates the maxim that solving the big problems exposes a myriad of smaller issues, and provides a number of new opportunities. It is also evident that there are research opportunities in almost every area of applied and fundamental science and engineering – and we have barely addressed economic issues and not even touched on the social aspects.

The Horizon system offers some valuable classification of research needs and opportunities:

- Horizon 2 problems mainly represent short term applied research topics, with immediate benefits, achieving implemented solutions over a 1-3 year range. These are the type of projects that industry have been most interested in and are currently being investigated to some degree.
- Horizon 3 problems represent longer term, more fundamental research projects, as there exist serious questions regarding either the scientific understanding, or the road to delivery of solutions. Given the risk-reward ratio of these research issues, joint government-industry funding is likely required to address them. They will also need close collaboration between different scientific/technical disciplines and progressive water industry partners.

Given the wide range of challenges outlined above, there will be a need for different key research and industry groups to focus on specific aspects. In Australia, we have a range of well-recognised expertise in areas such as micropollutants, virus removal and detection, risk assessment, membrane processes, and ecological impact of pollutants. The rapidly growing industry needs will help to further develop and expand Australian expertise in these areas.

From our perspective at the Advanced Wastewater Management Centre (AWMC), we intend to focus on topics related to our major research expertise in biological and chemical processes and in overall system optimisation and control engineering. Therefore, our main emphasis is on topics in Horizons 2 and 3 relating to pollutant characteristics and control, concentrate treatment including inorganic and organic fouling and overall system integration and optimisation. Significant progress has already been made on a number of aspects and will be reported separately in future.

Overall, there will be a significant need for R&D activities in many areas relating to water recycling. Given the rapid and widespread introduction of this concept in Australia, and the relative lack of expertise and experience in most other parts of the world, this provides excellent opportunities to not only establish leading research expertise in this field, but also develop strong industry know-how and experience that is applicable in many situations worldwide.

References

Bowyer, J. (2004). *The ecological significance of dissolved organic nitrogen from wastewater treatment plant effluents*. University of Queensland, Brisbane.

DAFF. (2004). http://www.affa.gov.au/content/output.cfm?ObjectID=F283DB44-6641-4723-8D4CC6B45E49F3A0, accessed 14/12/06.

Holt, J. K., Park, H. G., Wang, Y. M., Stadermann, M., Artyukhin, A. B., Grigoropoulos, C. P., Noy, A., and Bakajin, O. (2006) Fast mass transport through sub-2-nanometer carbon nanotubes. *Science* **312**(5776), 1034-1037.

National Coordinator for Recycled Water Development in Horticulture. (2005). *Water Recycling in Australia*. Land & Water Australia, Horticulture Australia Ltd, Arris Pty Ltd, Department of Primary Industries Victoria, CRC for Irrigation Futures.

National Health and Medical Research Council, and Council, N. R. M. M. (2004). *Water Made Clear: A consumer guide to accompany the Australian Drinking Water Guidelines 2004*. Australian Government, Canberra.

NRMMC, EPHC, and AHMC. (2006). *Australian Guidelines for Water Recycling: Managing Health and Environmental Risks*. National Resource Management Ministerial Council, Environment Protection and Heritage Council, Australian Health Ministers' Conference, Canberra.

Po, M., Kaercher, J., and Nancarrow, B. (2004). *Literature review of factors influencing public perceptions of water reuse*. CSIRO Land and Water, Melbourne.

Radcliffe, J. C. (2004). *Water Recycling in Australia*. Australian Academy of Technological Sciences and Engineering, Parkville.

Trewin, D. (2006). *Water Account: Australia 2004-05*. Australian Bureau of Statistics, Canberra.

Ying, G., Kookana, R., and Waite, T. D. (2004). *Endocrine Disrupting Chemicals and Pharmaceuticals and Personal Care Products in Reclaimed Water in Australia*. CSIRO Land and Water, Adelaide.